MATEC Web of Conferences **202**, 02009 (2018) https://doi.org/10.1051/matecconf/201820202009
AAME 2018

Performance Evaluation of a Resonant-integrated Pumping System

Lee Vincent Chieng-Chen

Faculty of Engineering and Science, Curtin University Malaysia, Sarawak

Abstract. Impedance pump is a simple valve-less pumping mechanism; it offers a low energy, low noise alternative at both macro- and micro-scale devices. It is also demonstrated to be a promising new technique for producing and amplifying net flow. There have been research studying the effects of series-connected impedance pump, where an increase in net flow is exhibited. In this study, an integrated system of conventional pump and impedance pump is introduced. This paper describes the performance evaluation of this integrated pumping system, with emphasis on the amount of amplification induced as a function of Womersley number (normalized excitation frequency) and normalized pressure head. Due to the nature of the resonant valve-less impedance pump, the integrated pumping system exhibits similar behaviour and characteristics as an impedance pump, such as the pulsatile nature of net flow. Results show positive outcomes where maximum amplification of 91.7% is demonstrated at resonance.

1 Introduction

Impedance pump is a very simple design that offers a promising new technique for producing and amplifying a net flow for both macro- and micro-scale devices [1, 2]. The impedance pump is a valve-less pump, which does not require impellers to operate. It is formed by joining a flexible tube to rigid sections. Asymmetrical excitation at a single location of the fluid-filled elastic tube will result in unidirectional flow due to the mismatch in impedance. Such pumping mechanism has shown to be highly sensitive towards the impedance in the tube, the location, and excitation frequency [1, 3-6].

The first demonstration of valve-less pumping through an impedance pump, was demonstrated by Gerhart Liebau in 1954, using an elastic tube connected to reservoirs at different heights [7, 8]. Following Liebau's work in 1954, there have been several research studying the underlying physics of the system, be it numerical or experimental. It was then, that the pump showed possibility in flow amplification. In recent years, study on sequential excitations on a single elastic tube shows promising results where increase in net flow is evident [9]. Other work on flow amplification includes design which incorporates multi-stage impedance pumping system [10] with flow enhancement of 69%.

Numerical study on flow amplification, integrating a steady and oscillating flow is also presented, where an estimated amplification of 120% is demonstrated [11]. The results are, however, not validated with any experimental data. With reference to that study, it shows that amplification of flow rate is indeed achievable with the aid of impedance pump. This study aims to prove this concept experimentally. The focus of this study is the amount of amplification induced, demonstrated as a function of Womersley number (normalized excitation frequency) and normalized pressure head during activation of the impedance pump.

2 Experimental methods and materials

The integrated pumping system utilises a modified version of the conventional impedance pump setup in Ref [10] with flow discharge at variable pressure heads. Figure 1 shows the schematic diagram of a modified two-stage open-loop impedance pump with flow discharge of variable pressure heads. Water inlet is connected in line as the silicone rubber tube to the source reservoir (reservoir on the left) as illustrated in the figure, from a water pump model DB-330A with power rating of 330 Watts with flow rate of 6 L/min. The water pump will transport the water from its source into the reservoir. Multiple flow discharges of variable pressure heads are configured on the deliverable reservoir (reservoir on the right) as illustrated, where the flow rates are measured. The pressure heads are configured at height difference of 0 to 60 mm (pressure head difference of 0 to 735 Pa) with 20 mm interval above the initial water level of 250 mm. These data will serve as the benchmarking data for the integrated pumping system. The elastic silicone rubber tube will then be excited simultaneously while water pump is transporting the water through the discharge. Flow rates, with additional effect from the excitations, are measured and analysed against the benchmarking data for comparison. The analysis of the flow dynamics will be in its non-dimensional form. Detailed analysis method are available in Ref [12].

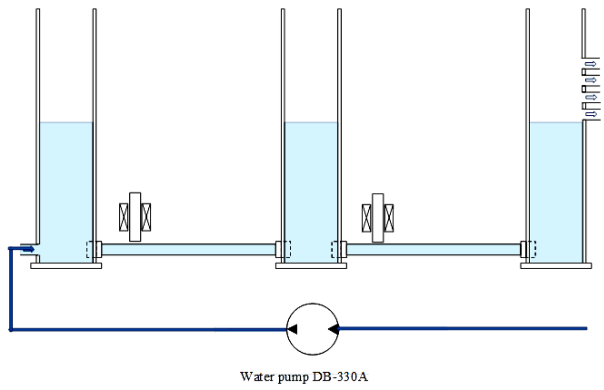

Figure 1. Schematic of experimental setup

3 Results and discussion

Amplifications with respect to different pressure heads, as a function of Womersley number are demonstrated. It is observed that active amplification (i.e. flow higher than 0%) is only within the range of Womersley number 59.4 to 92.0 (2.5 Hz to 6.0 Hz), as shown in Figure 2. This observed range of working amplification is similar to the working range of impedance pump as presented in Ref [10].

The amplified flow is observed to have similar characteristics as impedance driven flow where highly non-linear behaviour is observed. Similar to the impedance driven flow, the effective amplification range is shown to be at the Womersley number 70.3 to 88.1 (3.5 Hz to 5.5 Hz). This suggests that the effective amplification region coincides with the resonance of the system.

This phenomenon is due to the fact that the total flow rate is a summation of water pump flow rate and impedance pump flow rate as expressed in Equation (1)

$$Q_{tot} = Q_{pump} + Q_{impedance} \tag{1}$$

The water pump flow rate observes the Hagen Poiseuille law, as expressed in Equation (2) and impedance pump flow rate is as expressed in Equation (3)

$$Q_{pump} = \frac{\pi d^4}{128\mu l}\Delta P \tag{2}$$

$$Q_{impedance} = \frac{1}{\sqrt{R^2+S^2}}\Delta P_o \sin(\omega t - \vartheta) \tag{3}$$

where $R = \frac{128\mu l}{\pi d^4}$ $\quad S = \omega L - \frac{1}{\omega C}$

$L = \frac{4\rho l}{\pi d^2}$ $\quad C = \frac{\Delta V}{\Delta(\Delta P_c)}$

R denotes the fluid resistance term, S is the fluid reactance term, L is the fluid inertia term, and C is the tube compliance term. ΔP is the conventional pump pressure difference ΔV is the change in volume and $\Delta(\Delta P_c)$ is the change in pressure change within the elastic rubber tube, ΔP_o is the pressure change due to excitation, ϑ is the phase difference, and l is the length of elastic tubes.

Looking into the individual curve of different pressure heads, the curves show different characteristics as the pressure head changes. The curve of zero pressure head amplification is shown to be similar to the impedance driven flow where peaks are found to be at Womersley number of 59.4 to 102.9. Based on the characteristics shown on the output flow, it is shown that for amplification of flow at zero pressure head, the output flow behaves like impedance driven flow where it has high non-linear dependency towards the excitation frequencies.

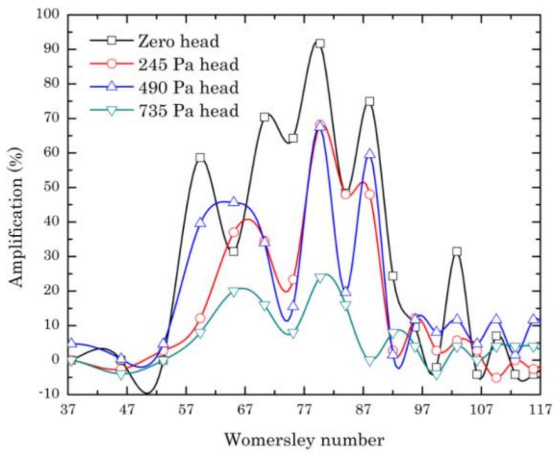

Figure 2. Flow amplification at different pressure heads

For pressure head of 245 Pa, flow is observed to increase as pressure head increases until it reaches the maximum pressure head where flow is observed to decrease from that point onwards. It is, however, observed that the amplified flow, again, peaks at Womersley number of 75.1 to 88.1, which is the resonance region of excitation for impedance pump. Flow is observed to be oscillating with minimal amplification for Womersley number ranges from 92 to 118.9. Amplification is apparent to be lower than the flow induced from zero pressure head. For pressure head of 490 Pa, the flow exhibits better amplification as compared to flow amplified at 245 Pa. Highly non-linear flow is observed at Womersley number of 75.1 to 88.1, maximum flow amplified under the resonant excitation is shown to be similar with the case of 245 Pa. Flow is observed to be oscillating with minimal amplification for Womersley number ranges from 92 to 118.9, similar to the previous case.

Low amplified flow is observed for the pressure head of 735 Pa. The flow is shown to have non-linear behaviour, similar to previous two cases. Amplifications are observed to be extremely low as compared to all previous cases. For all cases, the maximum amplification occurs at Womersley number of 79.7 (4.5 Hz), which is demonstrated to be the resonant excitation frequency of the impedance pump. It is also suggested that the excitation region of Womersley number ⩽79.7 is the amplification region; and that excitation region > 79.7 is the suppression region for the system. Hence, a much lower amplification is observed.

With reference to results presented in Figure 2, it is shown that the excitation region of interest is within the Womersley number 75.1, 79.7 and 84. A more in-depth analysis of amplification and pressure head is made on these three points of interest.

Figure 3(a) shows the normalized flow comparison between a normal flow and the amplified flow at Womersley number of 75.1. As shown in the figure, the trend for both curves is observed to be similar. The normalized pressure head characterises the pressure head in the reservoir, and it shows that as the pressure head increases, the flow reduces in an oscillatory manner. The flow is observed to reduce from zero pressure head till 0.1, then slight rise at 0.2 and decrease again at 0.3. Ideally, flow rates of a conventional pump show a linear decrease in magnitude against the pressure head. A sinusoidal behaviour is observed, due to the elastic nature of the tubes, that exhibits a moving boundary as opposed to a rigid tube with fixed boundary. Therefore, it is showed that even with a steady flow from a pump passing through an elastic tube, sinusoidal flow behaviour can be expected. The amplified flow is observed to behave the same way. Margin between the normal and amplified flow is observed to narrow down as the pressure head increases, indicating that the amplification effect reduces as the pressure head increases. Reduction in the amplification effect is seemed to be in a rather linear manner.

Figure 3(b) shows the comparison between the amplified and normal flow at Womersley number of 79.7. Amplification is found to be highest at this Womersley number, where an amplification of 91.7% is demonstrated. Based on the two curves, the margin of amplification is observed to be quite parallel from zero pressure head till normalized pressure head of 0.2. For normalized pressure head of 0.2, the increment gradient of amplified flow is shown to be higher than the normal flow, suggesting a profound amplification effect at that pressure head. For pressure head of 0.3 however, the amplification effect is shown to decrease drastically.

The comparison of amplified and normal flow at Womersley number of 84.0 is shown in Figure 3(c). Amplification effect is observed to be lower than 79.7. The amplification curve is observed to decrease gradually along the normalized pressure head from zero to 0.3; whereas for the normal flow, the trend is observed to reduce from zero pressure head till 0.1, followed by a hike in 0.2 and a drop again at 0.3. The amplification effect is however different from the previous two cases where the margin is shown to be quite parallel from zero pressure head to 0.1. From pressure head of 0.1 to 0.2 however, a drastic narrow margin is shown due to the hike in normal flow but for continual decrement for the amplified flow. From 0.2 to 0.3, the margin is shown to be parallel once again.

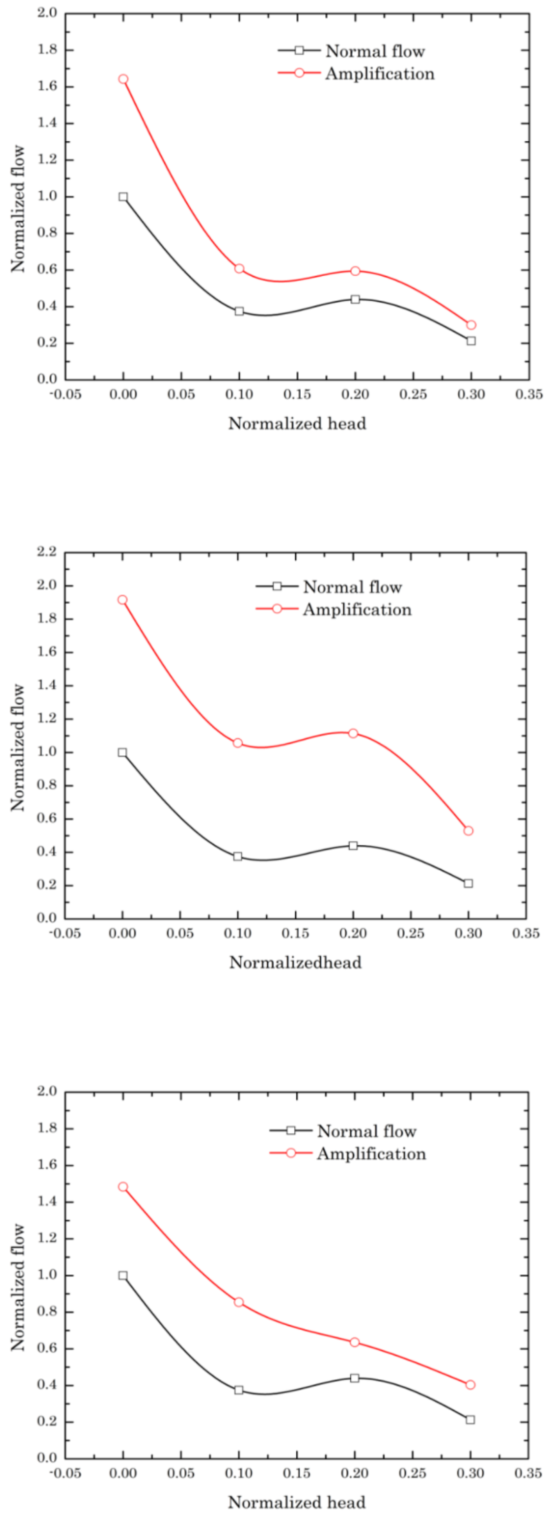

Figure 3. Flow amplification at Womersley number (a) 75.1 (b) 79.1, and (c) 84.0

In comparison to Ref [11] which reported an amplification of approximate 120% at resonance, current experimental study shows that flow amplification through integration of impedance pump is indeed possible. Maximum flow amplification is demonstrated at 91.7% at resonance. This shows that the amplification of flow is

https://doi.org/10.1051/matecconf/201820202009

rather well estimated. This deviation between the numerical and experimental result could possibly due to the de-coupled modelling between fluid and structure domain in Ref [11].

With reference to Figure 3, the amplified flow rates show some differences in its behaviours. This suggests that maximum amplified flow rate is achievable when the excitation frequencies coincide with the elastic tubes' natural frequency. This is clearly shown in Figure 3(a) and (b), where the amplified flow behaviours are similar to the normal flow. Hence, the excitation frequency plays an important role in determining the system's efficiency.

With reference to Equation (1) – (3), it is shown that the total flow rate is highly dependent on the impedance pump. Flow rate resulted from the water pump is basically constant throughout the whole process of the same pressure head. Flow rate from the impedance pump, is however, change with respect to time. Hence, a pulsation of flow will occur. It is shown, as well, that the amplification percentage reduces as the pressure head increases.

4 Conclusion

This study presents and introduces an integrated system of conventional pumping system and impedance pump for efficient pumping. Profound flow amplification is observed as an effect of the integration at the working frequencies region of 3 Hz to 6 Hz or Womersley number of 75.1 to 92.0. Impedance driven flow characteristics are observed in the amplified flow such as the sensitivity of flow towards the excitation frequencies and the non-linear behaviour of the flow. Maximum amplification is observed to be at resonant frequency of 4.5 Hz with an amplified flow of 91.7%. It is also suggested that the optimum pressure head for effective amplification in this study is 490 Pa.

References

1. I. Avrahami and M. Gharib, Computational studies of resonance wave pumping in compliant tubes, J Fluid Mech 608 (2008) 139-160.
2. D. Rinderknecht, A. I. Hickerson and M. Gharib, A valveless micro impedance pump driven by electromagnetic actuation, J Micromech Microeng 15 (2005) 861-866.
3. V. C.-C. Lee, Y. A. Abakr and K.-C. Woo, Dynamics of Fluid in Oscillatory Flow: The Z Component, Journal of Engineering Science and Technology 10(10) (2015) 1361-1371.
4. C. G. Manopoulus, D. S. Mathioulakis and S. G. Tsangaris, One dimensional model of valveless pumping in a closed loop and a numerical simulation, Phys Fluids 18 (2006) 017106.
5. A. I. Hickerson, An experimental analysis of the characteristic behaviours of an impedance pump, Ph.D. Thesis, California Institute of Technology, 2005.
6. S. Timmermann and J. T. Ottesen, Novel characteristics of valveless pumping, Phys Fluids 21 (2009) 053601.
7. G. Liebau, Über ein ventilloses pumpprinzip. Naturwissenschaften 41(1954) 327. (in German)
8. G. Liebau, Die stromungsprinzipien des herzens. Zietschrift f'r Kreislauf-forschung 44 (1955) 677–84. (in German)
9. M. Rosenfeld and I. Avrahami, Net flow rate generation by a multi-pincher impedance pump. Comput Fluids 39(9) (2010) 1634-1643.
10. V. C.-C. Lee, H. S. Gan, Y. A. Abakr and K.-C. Woo, Bulk Flow Behaviour of a Two-Stage Impedance Pump. Engineering Letters 22 (2014) 53-62.
11. V. C.-C. Lee, Y. A. Abakr and K.-C. Woo, Impedance Pumping System as Flow Amplification Device, Oral Presentation. In: 2011 International Conference on Applied Mechanics, Materials and Manufacturing, China, 2011.